In pursuit of perfecting the imperfect – Ceramic 3D printing process for Creating Unique Surfaces

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Abstract

In this thesis, a ceramic printing process is studied through experimentation of variables that influence creation of errors i.e. imperfections in the printed form of small cup-like models. The goal is to create interesting and organic surface textures by incorporating imperfections into products printed in a precise industrial fabrication.

I find the subject of organic imperfections created in fabrication processes fascinating. Thus the unique capabilities of ceramic printers in surface design has been a target of experimentation.

The content of this thesis is divided into the research phase where the creation of desired errors is explored and into the phase of serial print runs where the aim has been to reinforce and verify the findings by producing structurally similar forms that all are unique due to the errors created by the printing process.

The study was performed by using the Delta WASP 40100 clay printer with stoneware and porcelain as a starting material to produce the printed forms. Printer parameters were altered and individually studied for their influence in creation of errors.

Research phase indicated that the most important element what influenced the end product was the quality of clay. However, pressure and flow can be used to counteract the clay quality and in conjunction with layer height produce ultimately desired errors.

Whether the findings to create defined imperfections in the printed forms could be applied to a bigger scale, several different printed forms were produced through methods ranging from layer jumping, platform manipulation and gravitational depression. Experiments proved to be successful.

In conclusion,

The process producing defined errors on the surface of clay cups can be manipulated and controlled. Clay quality is essential producing end products successfully. Variables used to guide the clay quality and facilitate or nullify errors to ensure successful printing can be recognized. However, there is no definite settings for ideal printing results. Instead, variables must be calibrated to accommodate the quality and viscosity of the clay in such a way, that will result in the creation of desired effects.

Research question: Is it possible through controlled manipulation of certain variables to create deliberate errors during the ceramic printing process that influenced the outcome of the finished print?

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1 INTRODUCTION

The purpose of this thesis is to explore and understand the circumstances and factors that influence the printing process of ceramic objects in order to ascertain what factors play a role in the creation of printing errors.

This thesis is divided into two parts, first part is the research phase where the different factors and variables that affect the printing process and the creation of desired errors are studied. After analyzing the information gathered from the research phase serial print phase follows. In this second phase the goal is to produce serial print runs wherein every individual object displays unique surface errors. Controlling the errors and success of the research phase in understanding and applying the variables reliably creates possibility to produce desired errors deliberately and consistently.

All experimentation in this thesis will be conducted with the tools and options available within the 3D printer itself. Manual options and variables of the printing process are also experimented in order to create errors by simple adjustments the variables of the printer.

1.2 Background of the study

I find ceramic printing to be a fascinating technology which has a multitude of future applications. The more obvious ones are in architecture and sustainable development which was the delta wasp printers' original purpose (3D Printing Business Directory, 2021). However, this technology has a great value in the creative fields as well.

The background of this thesis is the previous experimental design course I took part in. During the course I realized the ceramic printer's unique potential to experiment surface design. I noticed how some errors appeared in the layer during the printing process: the clay extruding from the nozzle did not always line up with the underlying layer and thus created these organic looking errors in the form of pultruding folds and ripples. I found these errors very organic like many things in nature, a powerful contrast to the otherwise coherent and industrial layered pattern of the print (Figures 1.1 & 1.2).

(Figures 1.1 & 1.2) Test print created during the experimental design course. Interesting errors appeared at the bottom and top part due to apparent printing error, which sparked my curiosity.

It was very fascinating to see such breaking of order that fitted so well to the surface, the juxtaposition of chaos and order, organic and inorganic, natural and at the same time industrial. I wanted to study this and be able to control it so that it could be applied to future design projects. See Figure 1.3 below.

(Fig1.3) Examples of different printed forms with apparent impurities created during the printing process.

2 THEORETICAL BACKGROUND AND THE GOAL OF THE STUDY

2.1 Basic information on ceramic printing

The ceramic printer used throughout this thesis was the Delta wasp 40100 clay 3D printer that utilizes a technology called liquid deposition modelling (LDM) to extrude fluid-dense material into an affixed platform. This technique is effective in the printing of functional, end-use materials such as clay ceramics. The system is ideal Self-production and experimenting, due to its fast printing times, adjustability and ability to closely observe and adjust the printing process (Moretti, 2016).

Both the Delta Wasp printer and the LDM technology were developed by the Italian organization WASP, which stands for "World's Advanced Saving Project." Their mission statement and the original purpose of their printers was to create sustainable solutions to self-produce and help shape the world through the use of environmentally friendly materials (3D Printing Business Directory, 2021).

3D ceramic printing is a relatively new technology that works in a similar way to polymer and thermoplastic 3D printing with a few key distinctions. The printed material (clay) is in a fluid-dense state, which is deposited through the LDM extruder's nozzle in one continuous stream of clay that moves in a predefined pattern set by the spliced CAD model building the form up layer by layer. Filler material cannot be injected to support the building of the form, so one must be aware of gravity and the limitation of the material used. The clays natural elasticity, viscosity and the inadequate time for the material to dry during the printing process can result in compression of underlying form or collapse of the entire print. In all these cases the extruded material has a fundamental role in order to get final acceptable results (WASP, n.d.).

While researching the background and previous studies relating to the themes of this thesis, I found that there is an apparent lack of research of the aesthetically oriented, experimental side of this technology. Some examples of research in architecture about the facilitation of imperfections and errors exist (Gail Peter Borden and Meredith, 2018) as also in ceramic artist and WASP collaborations (Andreoli, 2016). However, none of which directly corresponded with the subject of creating unique surface textures through the means of printing errors.

The concept of deliberately incorporating errors into production processes that result in imperfect and unique products is not unheard of in Finland. In the 60's the famous Finnish designer Timo Sarpaneva developed together with professional glassblowers a techniques which introduced imperfections in his serially produced glassware (Sarpaneva, 2020).

There were many things I figured out and learned during the experimental design course that made me already familiar with the basics of the printing process and what to expect. But to be able to understand why exactly the errors appeared in the printing process I wanted to expand and deepen the research I had already started. My notes from the previous course are used as the basis to build up the research phase.

2.2 The goal

The main goal of this thesis was to understand how to create impurities consistently on the printed object which in a serial production successfully results in identical forms that all display unique differences on their surfaces due to the errors stemming from the printing process.

The approach of this study was to learn the whole printing process, different variables and conditions that affected in the process and its end result. The desired errors/impurities were created by manipulating the variables and parameters of the printer.

(Fig2.1) On the left, The standard 'ideal' printed form, devoid of any impurities. On the right, The same print with the desired errors, as in impurities in the form of ripples and folds.

The clay printing process creates a layered surface, which looks very industrialized and coherent, however, if there is an error in the printing process that causes some sort of propagating dynamic change within the form, the layers become out of sync and results in organic looking imperfect surface that breaks the otherwise precision manufactured look of the object (Fig.2.1). The area where the dynamic change originates from creates overlapping folds that slowly correct themselves in the subsequent layers. I call the error that this produces as the **ripple effect**.

The goal of this thesis is to intentionally create the ripple effect during the printing process, without ruining the printed object (Fig2.2). A deeper inspection into the error propagation and possible explanations for its occurrence will be discussed in Results section 6.

(Fig2.2) assortment of test prints, which display different multitudes of the ripple effect

3 METHODS AND MATERIALS

3.1 Research strategy

The research in this thesis was conducted using mixed method research which combined elements of quantitative and qualitative research approaches. I chose the mixed research because it offered a wide array of methods to comprehend and understand the phenomena under investigation by using appropriate data collection of both research approaches (Leavy 2017).

Qualitative approaches such as inductive research proved ideal for this research due to the limited preexisting literature of the subject at hand ie. emphasizing observations, recognition of patterns from which to draw conclusions and ultimately developing a theory (Streefkerk, 2019). Due to the explorative nature of the research, meaning-making process would be a useful tool for acquiring a depth of understanding and purposeful exploration of impurities that is described and explained through visual analysis of the printing process.

Quantitative research approaches used during this thesis included comparing and measuring data collected from sample prints, testing relationships between different variables in order to reveal patterns and correlations. In the research phase the goal was to create a sizeable collection of samples (statical overview) for the purpose of explaining the phenomenon (Leavy 2017).

The information in the research phase was gathered empirically, with conclusion drawn strictly from evidence-based observations, testing and deduction. Throughout the experimental research phase a coherent and structured record of all the test pieces was kept for future reference.

Background information and other relevant input was obtained through Interviews and discussions with various workshop masters who had extensive professional and experience-based knowledge in ceramic 3D printing. The largest contribution of information was given by Manuel Fonseca Martinez, the Workshop Master of the 3D printing workshop who provided substantial help in troubleshooting and gave great insight into the printing process.

3.2 Methods

The way I approached the research of the printing process was firstly, to identify all the possible factors that could affect the printing process. These included all the variables and parameters that could be adjusted within the WASP printer or controlled reliably, as well as noting the conditional factors that were outside of my control and either negate them or adapt to their properties.

The preliminary list of all the variables that were the subject of research because of their apparent impact on the creation of errors. The basic description and function of these variables were obtained through personal communication with Workshop Master Manuel Fonseca Martinez.

The compiled list of variables to be researched included:

- **Flow**. Speed of the crew mechanic that extrudes the clay from the nozzle. Default setting on the printer was set by the standard calibration of the Cura splicing software
- **Speed**. How fast the extruder moves and performs the printing. Default setting on the printer was set by the standard calibration of the Cura spicing software which was 35mm per second.
- **Pressure**. Which is used to force the clay from the container tank into the extruder. Default pressure was 0.4 bar
- **Layer height**. The distance between the extruder's nozzle and the printing platform that is calibrated through zmax (vertical maximum) before printing on a new platform. Predefined in the Cura splicing software. The default Is calibrating a minimal gap with zmax and setting the layer height to 1.2mm in Cura.
- **Clay quality** - The general properties of the clay that is mixed and loaded into the container tank and used as the printing material. Important factors in clay quality are moldability, adequate viscosity and evenness.

Briefly, the research phase was focused on the exploration of the different variables and on gathering data by printing test pieces with varying options trying to see which options work together and create the most desirable outcome in terms of errors.

I adjusted my approach later on after receiving new information based either on my own observations or discussions with Manuel Martinez.

3.3 Restrictions

The restrictions were imposed to reinforce the purpose of the thesis, to find out whether it was possible to create errors reliably within the printed form. In order to prove this the printer should be calibrated and made to produce a set number of objects and at no point **during** the serial printing process would any of the options or variables be modified. Providing that the result would be a set of structurally identical forms that all had unique surface errors, the reliability of the error-making process would be valid.

The restrictions were more laxed during the research phase due to the deductive nature of the experimentation. The study of variables required experimentation and adjustments during the printing process.

Overall restrictions that aimed to limit the scope of the thesis included:

- Using the 2mm LDM extruder nozzle throughout the research and serial printing process.
- Type of clay used. Majority of the prints were done with stoneware and porcelain clay.
- Restrictions on clay quality control due to the inability to reliably mix consistent and good print quality clay, mixing and evaluating clay quality by hand.
- Small and simple prints. All the printed objects were about 50mm in height and 40mm in diameter, enabling them to be quickly printed in 2-4 minutes. Negating the complexity and added time that a larger print would produce and allowing the production of large volume of test pieces. Simple prints enabled me to focus on observing the effects of the variables without adding new layers of complexity to an already volatile process.
- Limited modification in the Cura splicing software, which is the splicing program that prepared the CAD file for 3d printing. The splicing software enables complex modification of the printing procedure and sets the base value of several variables. Since it adds complexity to an already sporadic process, all the values will be kept at their standard setting, with the only exception of layer height, which will be modified through the splicing software due to ease of access.
- No utilization of g.code or grasshopper to modify the algorithm of printing files (Lazzari, 2020). I was informed by Janne Ojala that similar error processes could perhaps be programmed with these tools. Rather wanting to try to create errors by experimenting with the printers manual parameters and in the process learn as much about the cause and effect of ceramic printing.

The following restrictions that were set for final serial print runs to ensure and reinforce research findings:

- Simplifying the approach by limiting all the possible variables into the most crucial ones, only a few that were relevant in the creation of errors.
- Refraining from modifying or adjusting these variables during the printing process. The only way to guarantee the research to be valid, is to print a series of same object by precisely replicating the same conditions, resulting in the ripple effect.

3.4 Research questions

Due to the nature of my research, I approached the research question inductively to narrow the scope of study and explore the possible causes of the error phenomena. The primary research question was the following: **Is it possible through controlled manipulation of certain variables to create deliberate errors during the ceramic printing process that influenced the outcome of the finished print?**

At the very beginning of the research phase, I pondered whether it was possible to understand and control the ceramic printing process so that the errors created could be completely mitigated or if desired, applied controllably (Fig.3.1). This question spawned several sub-questions that related to either the research phase or the serial print phase.

The questions I needed answers in the research phase: **How do the different variables effect the printing process and whether it was possible to reliably control these variables?**

This question lead into the second question concerning the serial print phase: **Is it possible, utilizing the knowledge gathered in the research phase, to reliably serial print ceramic objects that are all unique?**

(Fig3.1) Printed forms from previous experimental design course that explored the incorporation of surface errors.

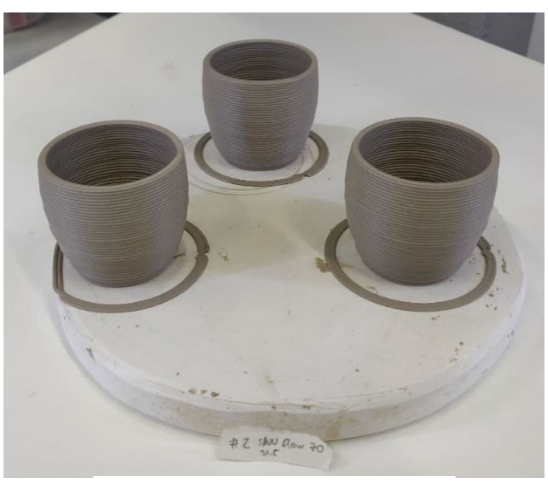
4 RESEARCH PHASE

4.1 Research phase

This section is composed of all the structured and compiled notes that were written during the research phase from observations and thoughts. Abstracting the whole process chronologically and further elaborating the findings in the results phase.

Based on my experience from the previous experimental design course, I had a basic understanding of how the printing process worked and how the main variables impacted the print. I began my research by reviewing my experimental design course notes as well as discussing optimal way to approach the research phase with Manuel Martinez. The first test prints were done with the previous courses print files to get accustomed to the whole process (Fig.4.1). Loading a new tank of stoneware clay, which I mixed according to the ceramic workshop master Tomi Pelkonen's guidelines and perceived as having good quality and viscosity.

(Fig4.1.) Reprinted forms of the previous course which were used in the beginning of the research phase



(Fig.4.2) Calibration prints

I made new spliced 3D prints that were cylindrical, with a slight negative curvature with a few different variations. The standard procedure before printing on a new platform was to calibrate the printers zmax, which means lowering the clay extruder as close to the printing platform as possible and relying on the preset layer heigh of the spliced file.

When I was researching single variables, my standard approach was to firstly print a reference piece with the standard options, from which I started to make small deviations with the selected variable. I always repeated the same print a total of 3 times to see if the results remained consistent (Fig.4.2). The first tests I conducted involved varying the distance between the extruding nozzle and the platform, changing the layer height between 1.2mm and 2mm, documenting and comparing the results.

These tests were followed by focusing on the flow variable, documenting the changes that happened when it was lowered and increased. The exploration of variables was progressing smoothly, until I noticed discrepancies between test pieces that were printed on different days despite having the same variable adjustments. I realized that the platforms unevenness plays a bigger part in the printing process than I first thought (Fig.4.3). Even the slightest change in elevation drastically alters results, because it changes the layer height. I counteracted this by printing on the most even surface I could find and printing all 3 test pieces on a smaller platform and at the exact same spot, nullifying the effects of the surface platforms unevenness (Fig.4.4). Results were documented and after that the print was destroyed and the process was repeated.

(Fig.4.3) Uneven platform produced different results of repeat prints

(Fig.4.4) Repeating prints in the same spot nullified the platforms unevenness

While focusing on the pressure variable, I found it to function similarly to the flow but with a larger impact (Fig4.5). I noticed that heavy manipulation of the machines pressure can result in pockets of air in the extruder, which resulted in unpredictable flow and pressure releases that destroyed the print.

(Fig4.5) Experiments of altering pressure levels during printing.

While continuing the research process I was still bothered by irregular results when reprinting test pieces from previous days, even after nullifying the platform unevenness. After some observations, I noticed the impact the clay quality had on the printing process. When the clay quality was ideal with adequate viscosity (wet, moldable, sticky) the errors appeared more regularly and generously. When the clay was flawed (dry, crumbling, inviscid) it had trouble keeping composure. See Figure group.4.6.

(Figure group.4.6). An assortment of test prints that display the effect of clay quality in the production of errors. (Which will be elaborated in the observations and results 4.2)

The wetness of the clay forced me to manipulate the zmax to create a wider gap between the nozzle and platform with very promising results. This was a good way to create interesting errors with adequately viscous clay creating space enough for the clay to divert from its path. With subsequent clay tanks the new, less viscous clay compositions changed the results of repeated prints and new calibration of variables had to be made to fit the clays properties.

Near the end of the research phase, I decided to experiment with uneven printing surfaces. Exploiting the sporadic factor that layer height fluctuation produces. One method to facilitate the desired errors was to create slight creases and elevation differences in the platform. I found that the elevation changes needed to be gradual and small, few millimeters at most. The errors are produced depending on the placement of the printing in the platform to overlap the creases and dips.

4.2 Observations and results

Once I felt confident enough with the results of the test prints of the research phase and further testing provided no new information, I moved on to compiling and analyzing the research. The big revelation I had while experimenting the variables was the importance of the clay in the overall printing process. When I started the research, my hypothesis was that by controlling the variables, I could find the perfect combination of settings that produced the desired errors regardless of outside factors. Turned out that the quality and viscosity of the clay is the most important factor and without sufficient way to consistently create similar quality clay, it is up to manipulating the other variables of the machine to accommodate the clays qualities and through this produce satisfactory results.

After noticing how much impact surface evenness has in the printing process, I experimented with the possibility of disregarding variable tweaking and opting to create the ripples with deliberate uneven platform in order to force the creation of desired errors. This proved to produce interesting results (Fig.4.7). However, although this was a simpler solution it was less applicable. Nevertheless I decided to move forward to serial printing with it.

(Fig.4.7) Errors produced by elevation changes

Much of the research revolved around finding the printing “sweet spot”. Creating a condition where the printing process is loose enough to give the extruding clay room to briefly divert from its path thus creating the error but being coherent enough to catch up and correct the error further in the printing process, as to not lose total cohesion and destroy the print.

I changed my approach for creating errors by studying how the clay quality responded to the manipulation of the variables.

How variables should be adjusted depending on the clay quality to produce errors ie. Imperfections		**Clay quality**	
Variable		**Bad quality clay**: Dry, crumbling, low viscosity	**Good quality clay:** wet enough to stick and be moldable. Adequate viscosity
Speed Default set by Cura Splicing software 35mm/s - 100% in printer		Impactful for ensuring successful printing when speed is lowered, giving more time for the clay to stick to the surface.	Little relevance, lower speed nullifies errors, higher speed has minimal effects on the creation of errors, but speed up the printing process. Most tests were performed with standard 100 speed
Flow Default set by Cura splicing software 100% in priner		Increasing the flow is crucial for helping the clay stick to the surface. High flow is an Important factor in facilitating errors in dry clay.	Ideal clay quality leaves room to play with the flow option. Reducing flow to as low as 30% proved effective in facilitating errors, this is due to the clays freedom to behave sporadically.
Pressure Adjustable within the printer Default 0.4 bar		Increasing pressure to upwards of 0.6 bar helps the clay in sticking to surfaces. Crucial factor in successfully producing errors on faulty clay.	Depending on how wet the clay is, the pressure can be set as low as 0.2 bar to facilitate errors. This produces slow, uncompressed deposition of the clay giving it room to divert from its path.
Layer height Can be either set in Cura or when calibrating zmax. Default set in Cura 1.2mm Ideal zmax >1mm		Layer height must be kept within 1.2mm to 2mm and compensated with increased flow or pressure. Going higher will result in failed print, due to the sluggish deposition and lag.	Increasing the layer height yields ideal errors when the clay is ideal. Can be increase upwards to 4mm with added pressure. The clay deposits sporadically in the beginning, until the process is able to catch up.

The provided exact figures of the variables that were extracted from the test pieces proved to be inconsequential due to the changing condition of the clay. However, the overall compiled data from the research phase gave a general idea how the variables should be set according to clay quality.

5 SERIAL PRINT PHASE

5.1 Preparation

Utilizing all the information gathered and analyzed from the research phase, using methods that guaranteed the most accurate results I was ready to start the serial printing phase. This phase is used as a proof of concept to verify the research phase findings.

The serial print test were performed with 2 differing forms that created the ripple effect through different methods:

- Rounded form, most experimented with during the research phase. Print runs with an even and uneven platform. 2 ways of facilitating errors. The uneven platform created for this purpose was made of plaster mold that had gradual differences in elevation, creases and slight pits.
- Sake cup form, less experimented, since it produced desirable results when the clay quality was ideal. The structure of cups facilitates ripple forming through gravity and the pressure of the extruded clay.

The preliminary procedure before printing was to test the clay quality by extruding large chunks of stagnant clay that might have dried up inside the extruder while it was not in use. To test the clays quality, I took the extruded clay and evaluated its viscosity, elasticity and overall stickiness based on how it felt when molded in my hand (Fig 5.1).

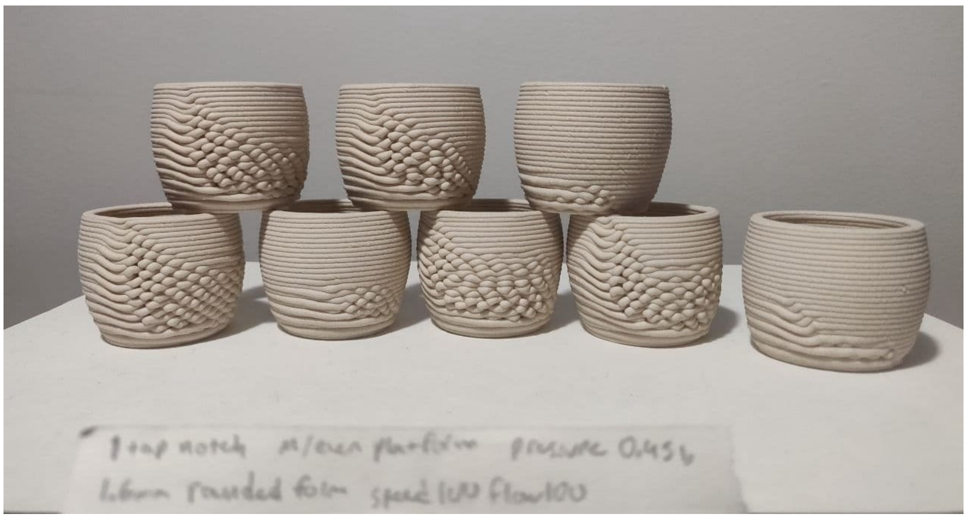
(Fig5.1) Running my fingers through the extruding nozzle at varying heights to test the clay quality and how it corresponds with varying layer heights before initiating the printing process. Index finger, small layer heigh. Middle finger, slightly increased layer height (optimal for errors with this clay composition) ring finger, increased layer height (too high, resulting in loss of control)

Once the clay felt consistent I began making standard calibration prints with the goal to create a perfect print. This print was used as a base which depending on the outcome and the clay quality would be manipulated by the variables to produce the desired ripple effect. When I was able to produce the ideal rippled print I replicated the print in all the 4 corners of the printing platform to see if the height deviation would alter the results. Once all four corner prints produced adequate ripples, I carried on with the actual serial printing run.

5.2 Serial printing process

Each serial print run was closely observed and catalogued. Once the printing process on the first form was finished, none of the variables were tweaked for the rest of the print run. There were a few occasions where the printing had to be paused, in order to extrude and discard uneven quality clay.

To ensure consistent results, I printed all pieces of the serial runs in quick succession, so the quality would not shift from disuse. Each print run composed of as many printed pieces that would fit the given platform. Most of the print runs were performed on different days and with newly loaded tanks of clay, which explains the change in clay quality.



(Fig.5.2 & 5.3) 1st and 2nd print runs. 1.6mm Rounded form | medium even platform | ~2mm layer height | Speed & Flow 100 | Pressure 0.45bar with suboptimal clay.

The first serial print run with the rounded form on an even, medium sized platform was successful. With the same calibrations, I performed another serial print run with corresponding results. The clay quality was not ideal, so I had to compensate by adding pressure and lowering layer height. All printed pieces in both runs have interesting errors with considerable variation and were completed without fail. Above Figures 5.2 & 5.3.

(Fig.5.4) 3rd print run with sake cup form | even large platform | ~2mm layer height | Speed & Flow 100 | pressure ~0.55 bar with suboptimal clay.

Due to the undesirably dry quality of the clay, pressure was added for the clay to stick to the surface of the platform and the subsequent layers. The print run produced Ideal results, that appeared quickly in the calibration process and persisted throughout the serial print run. Above Figure 5.4.

(Fig.5.5) 4th print run with rounded form. | Even medium platform | ~3mm overall layer height | Speed 100 Flow 130 | pressure 0.4 bar with optimal clay.

Printed with porcelain an ideal clay quality enabled the layer height to be set to ~4mm, minimizing compression and increasing sporadic deposition. The layer shift from the first layer to the second created the overshoot effect, which the ripples began radiating from, until the printing process gradually corrected itself. Above Figure 5.5.

(Fig.5.6) 5th Print run with rounded form| uneven platform |~3mm layer height | Speed 100 flow 85 | pressure 0.4 bar with optimal clay

Results were interesting and repeatable. Also the errors were ideal. Above Figure 5.6.

(Fig.5.7) 6th Print run with rounded form | uneven platform | Speed 100 Flow 90 | pressure 0.55 with suboptimal clay

Similar results to Figure 5.6. Except with suboptimal stoneware clay. The errors produced were much more restrained. Above Figure 5.7.

As a summary, wet clay is crucial for printing on the uneven platform due to dry clay having difficulties sticking into the creases of the surface. Wet clay sank into the creases and created spectacular results.

6 RESULTS

In these print runs, I tested out all the different approaches to creating ripples that I had ascertained from the research phase. The largest factor for errors was the clay quality and the layer height differential. Pressure and flow were essential to counteract the clays viscosity and deposition to the layer variance i.e. making the clay behave as a facilitator of the error.

In serial print runs on the even platform the ripple effect starts from the transition of the 1st layer to the 2nd layer, during which there is a small jump in the extruder that derails clay path, resulting an overshooting path that radiates through the subsequent layers until it is finally corrected by the process (Fig 6.1). The printing process requires enough layer height and low enough pressure to give extruded clay space to deposit without compressing the underlying forms.

(Fig6.1) The transitional layer jump derails (displaces) the clay from its path momentarily, thus creating the ripples that resonate in the subsequent layers.

Workshop Master of Mechatronics Janne Ojala suggested that this phenomenon may be explained through theories that exist in physics and signal processing such as propagating dynamic disturbance, like a wave or overshoot (Douglas, 2020).

Clay quality permitted, the uneven platform serial runs relied on the layer heigh difference to create uneven deposition that protrudes the clay out of place, resulting in spectacular ripple effects. Layers effected by gravity stoops inside the uneven surface, propagating throughout the form (Fig 6.2).

(Fig6.2) Layer height differential results in overlapping layers that slope downwards.

The principle for producing the satisfactory ripples in the sake cups was adjusting the nozzle to extrude clay with enough pressure to slightly stray from its set path. The curved bottom layers give way due to gravity and create interesting errors. The extruding clay layer pushes down the underlying layers that results in slight derailment of the sequential layer path and leads to the creation of the desired effect. Derailment point protrudes the clay outwards, creating an overlapping effect (Fig.6.3).

(Fig.6.3) Gravity causes the subsequent layers to slightly collapse the negative angles thus creating differences in layer height that facilitate the errors.

7 DISCUSSION

Overall, I was satisfied with the serial print runs since nearly every print had some level of the ripple effect. Observing the similar errors between different print runs that each had different variables and were printed on different days and with different tanks of clay it became evident that these errors can be created convincingly. While the clay quality might shift, the variables function as a counteraction and facilitate the errors.

The errors in the final prints varied from slight to severe and only 1/10 of the uneven platform prints failed to produce errors or were destroyed. Differences in the severity of the ripples between print pieces could be the result of slight differences in elevation, uneven clay quality or just the sporadic nature of the process. Nevertheless, I deemed the results satisfactory because I was able to consciously create the desired ripple effects despite the shifting quality of the clay by adapting the variables to counteract it.

When the clay viscosity was higher there was more room for the errors to appear and the risk of a failed print was lower. What mattered the most was the preliminary calibration to determine the clays properties and tweak the variables to fit them.

I had to perform the last remaining print runs with porcelain. Thankfully I did not find any difficulties or differences in its printing behavior compared to the stoneware clay that was used for all previous prints. If anything, the porcelain clays properties and mixture resulted in exception and generously occurring errors despite sources claiming to its difficulty in moldability (Brinck et al., 2021).

Rounded form print run on uneven platform produced spectacular results as well. But due to the random nature of the platform, some prints lost coherency and some had no errors at all. The uneven platform test runs resulted in more severe discrepancies between individual prints, but the ripple effect was much more defined.

The sake cups serial prints tested out how gravity and compression of negative angled structure could facilitate layer height variance that resulted in compelling errors. I Observed that the desired impurities of the print stem from the radical negative angles that occur in the first layers, once the layers start to go vertical, the force of the clay and gravity push the negative angled parts downward creating a larger gap, from which the resonance begins.

The technique to ensure ideal clay quality, was obtained too late to be implemented into the workflow resulting in the research process becoming unnecessarily more complicated. It was my failure that I did not consider the importance of clay quality earlier and did not modify my approach to working exclusively with ideal quality clay instead of having to figure out how to adjust the variables to fit the clays changing composition. When the unreliability of clay composition is taken out of the equation, the process becomes much simpler to control and the results more reliable.

8 CONCLUSIONS

Based on the evidence gathered during the research phase and the following outcome of the serial prints I concluded that it is indeed possible through manipulation of certain variables to create deliberate errors during the ceramic printing process that influence outcome of the finished print. This was shown by repeated serial print runs that displayed similar, reliable and repeatable results in the form of unique surface errors. That was the precisely the purpose of this thesis. The way this result was ultimately achieved was not what was expected while originally a definite setting was thought to produce ideal results. Instead, the settings must be calibrated to accommodate the quality and viscosity of the clay which must be then tweaked to create the desired effects.

In the study the question of how different variables affect the printing process in general was explored. Variables which are most relevant and have the biggest impact on the creation of errors as well as the variables effecting on the printing process itself were explored. Clay quality proved to be most important factor while it dictates how the variables should be adjusted to facilitate the errors.

The goal of this thesis to understand and control the apparent sporadic nature of printing errors through the research of selected variables, and then reliably applying it into the practice, brought a lot of new information about the subject such as:

- Importance of the clay quality in the creation of errors. The role of clay in liquid deposition modelling has been established before (WASP, n.d.) In all these cases the extruded clay material has a fundamental role in order to achieve final acceptable results. In the creation of errors the better quality (viscosity) the clay, the easier it is to work with and manipulate with the variables. It is also more forgiving to print with due to less risk of failure.
- This research also indicated that faulty clay can be worked successfully regardless whether it is used in normal printing or in producing errors deliberately. The suboptimal printing clay which might be too dry or too wet to adequately be printed can be adjusted with the variables to counteract its shortcomings.
- New information regarding the impact of the variables. Layer height is the most important variable to facilitate the creation of divergent and overshooting of clay. Pressure and flow can be used to counteract the clay quality and work in conjunction with layer height to ultimately produce desired errors. Platform stability can be used as a substitute for layer height variance for the creation of similar errors.
- There are several methods of manipulation to achieve the ripple effect, most of them concern layer height variance and ideal clay quality.
- The possibilities of creating interesting surface effects without the use of programs like grasshopper or complex modifying of the printing g.code are proved to be possible to create. Also, on the top of that it is possible to obtain cohesion and reliability/predictability during the printing process.

As a conclusion,

The process producing defined errors on the surface of clay cups can be manipulated and controlled. Clay quality is essential producing end products successfully. Variables used to guide the clay quality and facilitate or nullify errors to ensure successful printing was recognized. (Fig8.1)

Further, there is no definite setting for ideal printing results. Instead, variables must be calibrated to accommodate the quality and viscosity of the clay in such a way, that will result in the creation of desired effects.

The information gathered during this research will be used as the basis for my master's thesis. The next step would be to focus on perfecting the process of error-making and contemplating on its possible application in a surface design oriented project.

Possible future projects could include creating a standardized printing process where impurities can be facilitated onto whatever form that is printed. Exploring the full potential of this subject, by trying to create an even more reliable way of creating sporadic errors with the use of g.code or other 3d printing process altering algorithms.

(Fig.8.1) Compiled results of serial test runs that were the result of the findings of the research phase.

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